A Study on Vibration Control of Cylindrical Shells(円筒殻の振動制御に関する研究)

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論　文　内　容　要　旨

Chapter 1. Introduction

Cylindrical shells are used in many engineering structures such as the bodies of aircraft and space shuttles, coil drum of MRI (Magnetic Resonance Image) equipment, pressure vessels and tanks. The vibration of aircraft bodies generates large cabin noise and also leads to fatigue failure which is the direct cause of many aircraft catastrophes. The vibration of coil drum of MRI equipment also generates large noise in the test area. Mostof the vibration problems in these structures can be simplified as the vibration of cylindrical shells.

The objective of this thesis is to give a systematic study on the vibration control of cylindrical shells by using integrated distributed sensors and actuators, and different control methods. Application of distributed sensors and actuators to the vibration control of continuous structures has advantages. The coupling characteristics between a distributed sensor and a vibration mode to be measured can be improved by the optimization of the position and size of the sensor. The spillover due to a distributed actuator can be reduced by the optimization of the position, size and output force of the actuator. The integration of sensors and actuators into a structurs is also an important step in the realization of intelligent structures.

In this thesis, three different control methods are applied in the suppression of vibration excited by different kinds of disturbances. First the disturbance cancellation method is used to control the vibration excited by predetermined electromagnetic forces of coils inside the wall of the shells. Next the H_∞ and μ synthesis methods are used in the control of piezoelectric shells excited by two mini exiciters. At last a hybrid control method which is the combination of active control method and disturbance cancellation method is proposed and applied to the vibration control of a cylindrical shell excited by the base movement.

Chapter 2. Vibration Control of a Cylindrical Shell Used in MRI Equipment

This chapter studies the vibration control of the coil drum which is used to support the gradient magnetic coils in MRI equipment. The coil drum is a cylindrical shell with three groups of coils inside the wall of the shell. The coil drum is excited by the Lorentz force between the pulse current applied to the coils and the main magnetic field in the axial direction of the coil drum. The vibration of the coil drum generates high-level noises which have large influence on the performance of MRI equipment. In order to suppress the noise inside the coil drum, the vibration of the coil drum is to be controlled. In the coil drum, axisymmetrical modes are excited by the Lorentz force of z-coils and asymmetrical modes by those of x- and y-coils. To control these two types of modes two actuator models are proposed. Actuators generating in-plane forces are used to control the axisymmetrical modes and actuators generating bending moment to control the asymmetrical modes. Since the vibration of the coil drum is excited by predetermined forces, disturbance cancellation method is applied. The analytical model is established from the Flügge's equation of cylindrical shells and solved by using the modal analysis method. Simulation was carried out on the control of forced vibration excited by sinusoid and pulse signals. The frequency response shows that the vibration level is successfully reduced by more than 20dB in the frequency range of 400～1200Hz. It is also proved theoretically that a given number of modes can be controlled completely if enough number of actuators and control inputs are used.

Chater 3. Vibration Control of a Cylindrical Shell Using Disturbance Cancellation Method.

The purpose of this chapter is to verify the effectiveness of the control method of the former chapter experimentally in the control of shell vibration. The shell is a reduced-size model of the MRI coil drum. The model is made from two polyester films and two piezoelectric films (PVDF), which are pasted together in the order of PVDF－polyester film－polyester film－PVDF. The polyester films are used as insulators, between which the x-coils are inserted. For convenience the y- and z-coils are not considered in this model. The copper-nickel electrodes on the surfaces of the PVDF films are divided into several parts so that different parts can be applied with different voltages. When the two layers of PVDF on the inner and outer sides of the same part are applied with in-phase voltages, they generate a distributed resultant force in the area and this part can be used as a distributed in-plane force actuator. When the two layers of PVDF on the inner and outer sides of the same part are applied with 180° of-out-phase voltages, they will produce a distributed resultant bending moment in the area and this part of the shell can be used as a distributed bending moment actuator. In this chapter, two parts of the shell are used as bending moment actuators so that no external actuators are needed. A superconducting magnet is used to generate the main magnetic field in the axial direction of the coil drum. The vibration of the shell is excited by the Lorentz force of the coils inserted between the two layers of the polyester films. Experiment and simulation of vibration control were carried out when the shell was excited at the resonance frequencies of three main modes. The results show that the disturbance cancellation method in combination with the piezoelectric film actuators can successfully suppress the forced vibration of the shell and that the minimum amplitude of controlled vibration varies for different modes. The relation between control effect and the size, position and output magnitude of the actuators is also discussed.

Chapter 4. Active Vibration Control of a Cylindrical Shell Using Distributed Piezoelectric Actuators

This chapter presents a study on the vibration control of a piezoelectric cylindrical shell by using integrated piezoelectric actuator and H_∞ control theory. The cylindrical shell system consists of two layers of piezoelectric films pasted directly together. Since there is no insulator between the two piezoelectric films, only out-of-phase voltages can be applied to them and only bending moment actuators are available. In this model a part of the shell wall is used as a bending moment actuator. The state equation is established by means of the modal expansion method used in Chapter 2. The controller is designed by applying H_∞ robust control theory. The shell is vertically mounted on a stable base with a clamped lower end and free upper end and excited by a pair of mini exciters which are set 180° apart in circumferential direction. The two exciters are driven 180° out of phase so that the circumferentially odd modes are excited. Since feedback control method is used, sensors are needed to measure the response of vibration. In this chapter, a gap sensor is used to measure the displacement of a point on the shell surface. Numerical simulation and experiment were carried out on the control of forced vibration when the shell is excited at the resonance frequency of mode $(i, j) = (1, 5)$, where i and j are axial and circumferential wave numbers. The results show that the amplitude of the forced vibration excited by unknown disturbances can be decreased to one forth of the uncontrolled vibration by using this control method.

Chapter 5. Active Vibration Control of a Cylindrical Shell Using Distributed Piezoelectric Sensors and Actuators

This chapter studies the application of integrated piezoelectric sensors and actuators to the vibration control of a cylindrical shell. The experimental model used in this chapter has the same geometrical and physical parameters as that of the former chapter. One part of the shell wall is used as a bending moment actuator and another part is used as a distributed sensor. The output equation of the distributed piezoelectric sensor is deduced form the electric boundary conditions of piezoelectric materials and verified in the experiment. Modal expansion method is used in the establishment of state equation of the shell system and H_∞ robust control theory is used in the design of controller. The controller is then improved by the μ-synthesis method so that it satisfies the given control performance and robust stability. The same experimental setup as that of the former chapter is used. The shell is excited by two mini exciters driven in phase so that the circumferentially even modes are excited. Simulation and experiment are carried out on the control of forced vibration of the shell when it is excited at the resonance frequency of mode $(i, j) = (1, 4)$. The results show good agreement between simulation and experiment, as well as the good control effect of the method using distributed sensors and actuators in conjunction with robust control theory.

Chapter 6. Vibration Control of a Cylindrical Shell Using a Hybrid Control Method

In this chapter a new hybrid control method which is a combination of active control and disturbance cancellation method is proposed. The active controller and disturbance cancellation controller are designed independently. The H_∞ control and μ-synthesis theory are used in the design of the active controller. The active control input is calculated from the sensor output and active controller while the disturbance cancellation input is calculated form disturbance signal and disturbance cancellation controller. The two independent control input are added together and the sum is used as the input of hybrid control. The shell is constructed from a polyester film in the middle surface and two piezoelectric films, one on each side. Two parts of the piezoelectric films are used as inplane force actuators. The shell is vertically mounted on a slip table and excited by the horizontal movement of the table. An acceleration sensor is used to measure the vibration of the slip table, which is used as the disturbance signal needed in the calculation of disturbance cancellation input. A photonic sensor which moves together with the slip table is used to measure the relative displacement of a point on the surface of the shell, which is used as the feedback signal. The active control, disturbance cancellation and hybrid control methods are used, respectively, in the simulation and experiments and their results are compared. The results show that the hybrid control is more effective than each individual control method.

Chapter 7. Conclusion

Five subjects on the vibration control of cylindrical shells have been studied in this thesis. From the simulation and experimental results, the following conclusions can be obtained.

1. The flexible piezoelectric films can be used as distributed sensors and actuators in the vibration control of structures with curvature such as cylindrical shells.

2. Disturbance cancellation method can be used in the control of vibration excited by predetermined disturbance or disturbances which can be measured. Theoretically a given number of modes can be suppressed completely when enough actuators and control inputs are used. In the control of vibration induced by unknown disturbances, active control methods are needed. When the disturbance cancellation method and active control method are combined, better control effect be achieved in the control of vibration induced by predetermined disturbances or disturbance which can be measured.
3. This thesis gives a fundamental study of intelligent structural systems with integrated sonsors and actuators. The possibility of intelligent cylindrical shells with integrated sensors and actuators was proved in both the simulation and experiments.

審 査 結 果 の 要 旨

航空機の機内やMRI装置の騒音を抑制する技術の開発が重要な課題となっている。しかしこれには多数の振動モードと固有振動数を有する円筒殻の振動を抑制するという困難な問題を解決する必要がある。

本論文は，円筒殻の振動を抑制するため，圧電アクチュエータを用いた振動制御を行った研究成果をまとめたもので，全編7章よりなる。

第1章は緒論である。

第2章では，MRI装置傾斜磁場コイルドラムの複雑な振動現象を解明し，振動を抑制する方法を提案している。軸方向の強い静磁場中で任意方向の傾斜磁場を発生させるため，コイルに流すパルス電流により生じるローレンツ力で，励振されるコイルドラムの振動モードを明らかにし，それを面内力とモーメントを発生できる2種類の圧電アクチュエータにより相殺できることを理論的に示している。これは有用な知見である。

第3章では，MRI装置傾斜磁場コイルドラムの縮小モデルをポリエステルフィルムと圧電フィルムを用いて製作し，超伝導マグネットによる強い静磁場中でローレンツ力により励振させ，外乱相殺法で強制振動を抑制できることを実験的ならびに理論的に示している。

第4章では，曲げモーメントを発生する圧電フィルムアクチュエータで円筒殻の強制振動を，ロバスト性を有するH_∞制御理論に基づいてアクティブ振動制御できることを理論的ならびに実験的に明らかにしている。この方法は，任意の振動を抑制することができ，工学的に重要な成果である。

第5章では，圧電フィルムを用いて分布センサとアクチュエータを有する複合円筒殻を作製し，円筒殻自身が振動の発生を感知し，円筒殻自身が力を発生させ振動を抑制するシステムをロバスト性のよいμシンセシス理論に基づき構築できることを示している。これは振動が生じない軽くて薄い知的な複合円筒殻を創製できる可能性を示した貴重な成果である。

第6章では，外乱相殺法とμシンセシス理論に基づくアクティブ振動制御法を併用することにより，分布圧電アクチュエータで円筒殻の任意の強制振動を最も効果的に抑制できることを示している。

第7章は結論である。

以上要するに本論文は，円筒殻の振動を分布圧電センサとアクチュエータを用いて外乱相殺法とロバスト性のあるアクティブ振動制御法に基づき抑制できることを理論的ならひに実験的に，振動しない知的複合円筒殻の設計法を確立したもので，機械電子工学の発展に寄与するところが少なくない。

よって，本論文は博士（工学）の学位論文として合格と認める。